Kinematics of Distant Galaxies from Keck

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Abstract. DEEP is a two-phase spectral survey of faint field galaxies with the Keck Telescopes. The goals include exploring galaxy formation and evolution , mapping distant large scale structures, and constraining cosmology. DEEP, since its inception in the early 1990's, has been distinguished by an emphasis on studying the kinematics and masses of distant galaxies. The major DEEP survey in the second phase (DEEP2) is scheduled to begin in 2002 and will mainly aim for a sample of 50,000 galaxies to $I \sim 23$. Until then, the first phase of DEEP science programs will have been concentrating on using existing Keck spectrographs to undertake spectral surveys of over 1000 galaxies that have also been observed with HST. I will highlight the study of rotation curves of distant spirals; the fundamental plane of faint, high-redshift E/S0s ; the narrow velocity widths seen in luminous blue compact galaxies; and the diversity of kinematics seen in a small sample of high redshift ($z \sim 3$) galaxies. These DEEP pilot programs have clearly demonstrated the feasibility, importance, and potential of using kinematics to better understand distant galaxies.

1 What is DEEP?

The first decade of the 21st century promises many new surveys of distant galaxies, especially with the advent of a suite of new 8-10 m class, ground-based, optical telescopes. Besides adding critical redshifts to data from space and other wavebands, the higher S/N and spectral-resolutions affordable with 8-10m telescopes provide three new and quite powerful diagnostics for the analysis of distant galaxies: internal velocities (i.e., kinematics and hence dynamical masses when size is also measured); chemical abundances; and star-formation-rate and stellar-population-age estimates. Compared to the traditional parameters of counts, colors, luminosities, and clustering properties of distant galaxies, these new diagnostics yield independent probes of galaxy properties in the early universe and have solid links to theoretical simulations of galaxy formation. Moreover, since both galaxy evolution and their large scale patterns involve a complex interplay of diverse galaxy classes, environments, and physical mechanisms and because precision cosmology via the volume test requires averaging over the fluctuations due to large-scale clustering, very large samples are essential to extract reliable results.

To meet the challenge, DEEP[1] was initiated over 9 years ago as a spectral survey of 50,000 [2] faint field galaxies , using the Keck II 10-m Telescope with a new spectrograph DEIMOS [2] [3]. The use of DEIMOS provides a clean division of DEEP into two parts or phases. The first is a set of pilot-style surveys of relatively small samples (10's - 1000) of galaxies. These pilot surveys exploit the pre-DEIMOS spectrographs available on Keck and were designed to determine feasibility and to refine the scope of DEEP2. DEEP is distinguished by aiming to gather internal kinematic data in the form of rotation curves or linewidths, as well as spectral-line measurements sensitive to star formation rates, gas conditions, stellar-population ages, and metallicity.

2 DEEP Highlights on Kinematics

To maximize the scientific returns for the small samples from our phase-one, pilot surveys, we only observed fields where HST WFPC2 images already exist, including the HDF and flanking fields [6], [13], [19], [29]; the Groth Strip Survey (GSS) [10] [20] [28] [31]; and Selected Area 68. Such HST images provide not only morphology and photometry but also the structure, size, and inclination data needed to convert kinematic observations from Keck into direct measures of dynamical mass.

The DEEP data reach to $I \sim 24$ and confirms that DEEP2 is feasible and that kinematics and masses will be worth the extra effort [11]. I will highlight our studies of distant spirals via rotation curves; luminous red spheroids and blue compact galaxies via velocity dispersions; and a few high redshift ($z \sim 3$) "Lyman-drop" galaxies for which spatially-resolved kinematics is possible.

2.1 Rotation Curves of Distant Spirals

As seen inf Fig.1, we have clearly demonstrated that emission-line rotation curves of likely spirals can be measured with Keck's low resolution spectrograph (LRIS: [17]) to redshifts near $z \sim 1$ for galaxies as faint as $I \sim 22$ with 1–2 hour exposures [29]. Our new sample of about 100 rotation curves [30] [31] support the original conclusion that the optical Tully-Fisher relation for spirals near redshifts $z \sim 1$ show only modest (< 0.6mag) changes relative to that seen locally[28], [29]. These results appear on the surface to disagree with the claims for more extensive evolution of 1.5 to 2.0 mag [21] [23] [15], but the differences may reflect the selection criteria adopted. While our high-quality Tully-Fisher sample included galaxies that were slightly elongated and resolved along the slit, i.e. larger disk systems, the other samples were generally limited to very

[1] DEEP: Deep Extragalactic Evolutionary Probe; more details on participants and programs of DEEP can be found at URL: **http://www.ucolick.org/ ∼deep**

[2] our original goal of 10,000 has been revised upwards to improve significantly the reliability of cosmological tests and of large scale structure studies

[3] DEIMOS: DEep Imaging Multi-Object Spectrograph; more information is provided at URL: **http://www.ucolick.org/ ∼loen/Deimos/deimos.html**

blue or strong emission line targets, some of which may be very compact. We are currently expanding the completeness of our kinematic sample by including emission-line velocity widths in our studies (see contribution by B. Weiner). More solid conclusions on the Tully-Fisher relation (velocity vs. luminosity), as well as that of other scaling relations when one adds size or surface brightness, are critical to test whether various theories of disk formation are correct[3].

2.2 Spheroid/Bulge Evolution

We have undertaken several approaches to explore the evolution of luminous early-type galaxies, two of which exploit kinematics. In the first study[8], the luminosity function of over 100 early-type galaxies (E/S0) was derived, where the early-type class was selected on the basis of B/T being larger than 0.4; low levels of asymmetries; and high levels of smoothness using the GIM2D software for structural parameter extractions [24]. Keck redshifts were complemented by photometric redshifts. The main result is that there is evidence for roughly 1 magnitude of luminosity brightening back to redshifts $z \sim 1$, but otherwise no evidence for any dramatic drop in number density [8]. This result supports hierarchical models of galaxy formation in an open or accelerating universe rather than a high-Ω one (e.g., SCDM), in which early-type galaxies are presumed to have formed via merging of spirals in significant numbers since $z \sim 1$. In the second work [7], a more detailed study was made of the blue E/S0s. Kinematic information, including some very high resolution velocity widths as measured with an Echelle system (ESI: [22]), were used and we found nearly all to be low-mass systems, rather than bonafide massive E/S0 galaxies undergoing intense star formation.

In the third study[4], we explored the fundamental plane (luminosity: size: velocity dispersions) of 35 galaxies using LRIS data and found evidence for nearly 2

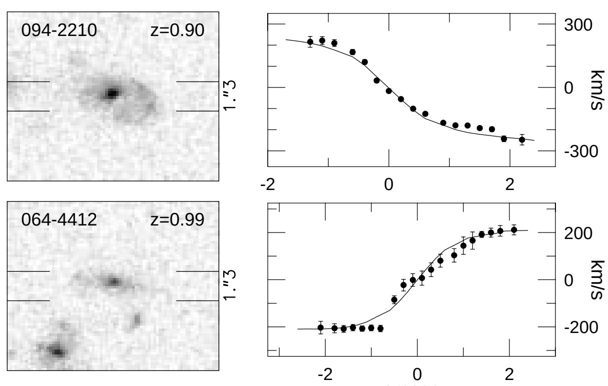

Fig. 1. Examples of the rotation curves measured for two high redshift galaxies [29], the upper with total $I \sim 21.4$ and the lower with $I \sim 22.4$. Besides the ID and redshift at the top, the images show the orientation and width of the slit.

mag of luminosity brightening back to redshifts $z \sim 1$. This amount would nominally suggest recent formation, if one adopts only passive evolution after a single burst of star formation, but oddly, the colors of these galaxies were moderately red. This result was confirmed by a fourth[12], purely photometric study of the luminosities and colors of luminous bulge subcomponents rather than the entire galaxy. While the size-luminosity relation indicated nearly the same amount of luminosity evolution ($\sim$ 1.5mag), virtually all bulges were nevertheless found to be very red (restframe $U - B \sim 0.5$). A possible explanation for this paradox would be that a very metal-rich, old stellar population is later contaminated by small amounts of bluer young or metal-poor stars.

2.3 Luminous Blue Compact Galaxies

Though spatially-resolved rotation curves are preferred, most faint galaxies are too small to yield more than linewidths as kinematic data. Except for galaxies bright enough to yield *absorption* linewidths, emission lines are used (see contribution by B. Weiner). Assuming linewidths are reliable measures of the true gravitational potential (after an upward correction of 40% [21],[27] to match HI or Hα values of kinematics), and adding HST sizes, we are able to obtain masses.

The masses of blue compact galaxies have been found to be especially interesting. For some, we find that luminosity can be a poor gauge of their masses. Though many have the luminosities of massive galaxies(L*), their velocity widths (σ) may be smaller than 30 km-s^{-1} as seen in the line profiles shown in Fig.2 [9], which were measured using the high resolution echelle spectrograph (HIRES:

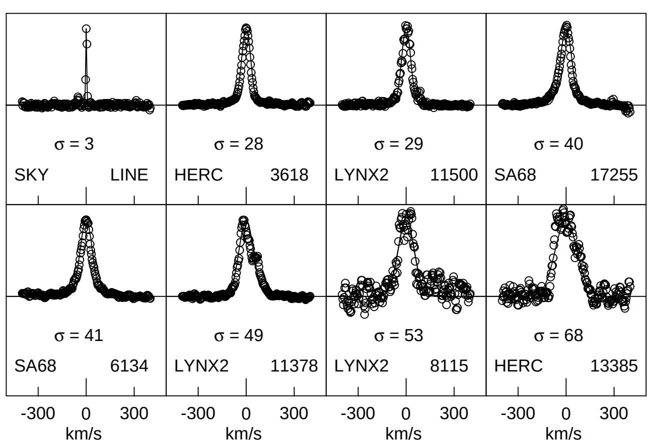

Fig. 2. Panel of HIRES [32] emission line profiles from a sample of luminous (L^*) blue compact galaxies at redshifts $z \sim$0.1–0.7 [5]. The σ are the FWHM/2.35 velocity widths in km s^{-1}. The dynamic range of the M/L in rest-frame B for these compact galaxies spans a factor of 45. The HIRES instrumental profile is shown in the upper-left panel.

[32]) . The resultant masses are very small and yield M/L ratios that span a wide range [5], [6], [19]. Our results suggest that some luminous blue compacts may be the progenitors of quiescent spheroidals today; that the down-sizing scenario [1] may apply to these galaxies [6]; and that such galaxies seen at $z < 1$ may be lower-redshift counterparts to the Lyman-drop galaxies seen at higher redshifts $z \sim 3$ [25]. A key point is that optical luminosities and mass are seen to be poorly correlated for this sample, i.e. stable and constant M/L may be a poor assumption at least for some classes of galaxies. This result clearly demonstrates the necessity, usefulness, and promise of kinematics as an important new dimension to discern the evolution of different galaxy populations.

2.4 High Redshift $z \sim 3$ Galaxies

A major advance with Keck has been the dramatic demonstration that galaxies chosen by multicolor photometry to be at very high redshift ($z \sim 3$) are confirmed to be so spectroscopically [25]. The DEEP team has extended the pioneering efforts in the Hubble Deep Field (HDF) [26] by pushing over one magnitude fainter; using redder "dropouts" to reach higher redshifts and higher levels of completeness; and adopting higher spectral resolutions to improve kinematic measurements [13]. Small motions observed from spatially-unresolved velocity widths [13] [18] and spatially-resolved kinematics indicate that some $z \sim 3$ galaxies appear to be small-mass systems that become dwarfs today or that later merge to form more massive galaxies [13], instead of being only the cores of massive galaxies in formation (which should yield high motions).

3 Summary

The main theme that arises from our DEEP pilot programs is that galaxy evolution is a complex problem. Galaxies are diverse in size, luminosity, structure, etc.; are composed of subcomponents which may experience different star formation and dynamical histories and evolution; and reside in a wide range of environments involving different physical mechanisms for their evolution. We have established that kinematics are both feasible with 8-10 m class telescopes and valuable for understanding distant galaxies. For example, we find relatively little evolution in the Tully-Fisher relation or disk surface brightness [23] to redshifts $z \sim 1$, as well as little evidence for evolution in the fundamental plane, volume density, or luminosity beyond that expected from passive evolution for early-type galaxies to $z \sim 1$. The colors of the spheroids and bulges are, however, redder than expected and thus a puzzle. On the other hand, luminous blue compact galaxies appear, whether at low redshifts $z < 1$ or at high redshifts $z \sim 3$, to have very low dynamical masses and are suggested to be possible progenitors of quiescent low-mass spheroidals today or the building blocks of larger galaxies rather than massive ellipticals undergoing formation via monolithic collapse.

The lessons from our DEEP phase-one pilot programs indicate great promise for our main survey DEEP2 of 50,000 galaxies. Such large numbers are vital for analysis after subdivision of the full sample by a wide range in luminosity, size, M/L, structure, redshift, and environment. More relevant to this conference, we are optimistic that the kinematic data will yield new studies that rely on mass, including mass functions; M/L functions; Tully-Fisher, Fundamental Plane, and other scaling law evolution; mergers rates; dark matter distributions (halo vs disk; large scale structure vs mass); and precision cosmology (velocity function vs volume tests; estimates of the equation of state [16]).

Acknowledgements: DEEP was initiated by the Berkeley Center for Particle Astrophysics (CfPA), and has been supported by various other NSF, NASA, UC, and STScI grants. The senior members of DEEP have managed the project, but I would like to give special thanks to our talented pool of more junior astronomers over the years (see DEEP URL for names), without whom the results presented here would not have been possible.

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